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Single Frequency Diode Pumped Solid State Lasers

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Introduction

Our original project goal was to develop a 1.06 micron, 5 watt single frequency, injection-locked laser. Both CW and Q-switched operation were required and we anticipated that Pound-Drever-Hall stabilization could be used for both tasks. A portion of the master oscillator used for injection locking was needed as a low-power frequency reference for LIDAR work.

We expected that we might optimistically be able to obtain about 25% slope efficiency using diode pumping which implied a required pump power of at least 20 watts. Earlier we had built some linear oscillators that consisted of a multiple-bounce optical path within a single block of Nd:YAG. Each "bounce point" required an individual diode pump and coupling optics. We anticipated that this architecture would not be easily scaled to high powers much above the 5 watt level so we decided to commit to an architecture that might utilize the recently available high power (10 to 20 watts) diode arrays. We decided to couple these arrays to one or more active Nd:YAG elements using optical fibers. We felt that this approach had several advantages. These included

a) low cost per optical watt for diode bars,

b) removal of the large diode bar head load from the vicinity of the laser oscillator. We expected this might reduce mechanical noise induced by the water cooling of the diodes and reduce the mechanical complications of mounting diode arrays near the laser resonator, and

c) potential of scaling to high powers by clustering of fibers.

The disadvantages of this approach are manifold but the most severe problem is that this fiber-coupled source is not a very intense source and is many hundred times diffraction-limited. This makes it difficult to efficiently couple this source to a TEMoo laser cavity mode.

The final difficulty that we anticipated in scaling to high powers was the problem of power loss due to stress-induced birefringence. Earlier reports in the literature of attempts to use fiber coupled diodes for end-pumping indicated that oscillators that provided TEMoo, polarized output were severely limited by stress birefringence as described by Koechner[1].

Proposed Embodiment

The following describes our intended solution to the design problem.

Pump Source

A pair of SDL 3490-S 15 watt diode bars were selected as pump sources. The diode bars have 12 individual emitters, each with a highly asymmetric output that is highly-divergent but nearly diffraction-limited in a plane perpendicular to the diode junction and a moderately divergent, but 100 times diffraction-limited output in a direction parallel to the junction. Each emitter is 200 microns in width, with a center-to-center spacing of 800 microns. Therefore, it is possible to couple each emitter into an optical fiber. However, if each emitter were simply butt-coupled into a single 200 micron diameter fiber, the resultant output would be an 800 micron diameter bundle of fibers with an output distributed into a large numerical aperture (NA) of .45. To partially maintain the brightness of each emitter and thereby lower the divergence of the output from each fiber, a 300 micron diameter fiber microlens is placed in front of the row of emitters to collimate the illumination in the diffraction-limited direction. This drastically reduces the average angular spread of the output from the fiber from an NA of approximately .45 down to an NA of .12. The

disadvantage of this technique is that some space is required for the lens, thereby requiring a power coupling fiber slightly larger than the emitter width.

The resultant illumination from the 12 individual fibers from each diode bar array was to be routed to the laser head for pumping the ring oscillator. A schematic diagram of this assembly is shown in Figure 1.

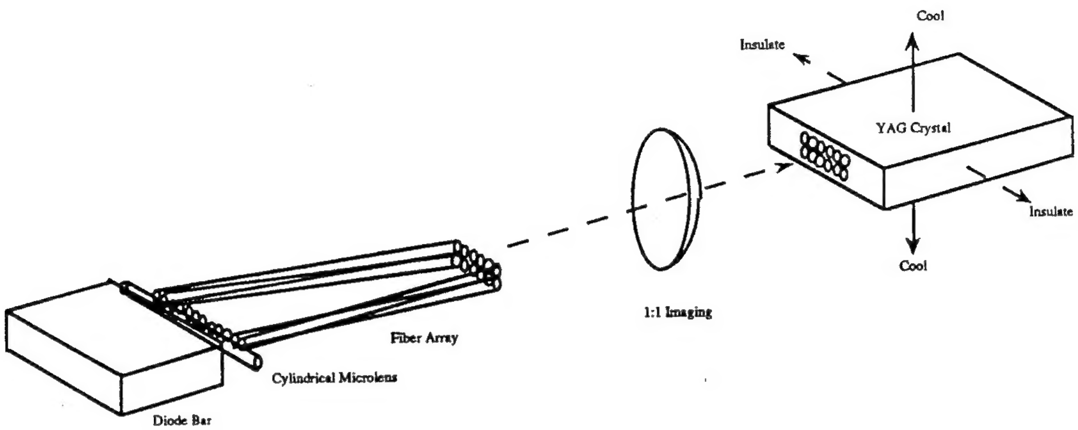

Figure 1. Rectangular end-pumped slab architecture for reduced stress birefringence. Both ends of the slab are pumped for a more uniform thermal profile.

Ring Oscillator

The key to high slope efficiency in laser oscillators is to manipulate the shape of the oscillating cavity mode and the incident pump mode for the greatest overlap within the laser crystal. A quantity for evaluating the quality of pump and cavity mode overlap has been defined by Kubodera, et. al[2]. and this quantity is defined as the "mode coupling efficiency", the value 1.0 representing perfect mode overlap. The laser slope efficiency is directly proportional to this number; for low-loss YAG cavities, the laser slope efficiency is approximately one-half of the mode coupling efficiency. The diffraction-limited cavity mode is easily manipulated to the desired size, while the relatively incoherent illumination from the fiber bundle is less easily reshaped. A considerable amount of care is required to efficiently couple this diode light power into 1.06 micron oscillator power.

The end-pumped rod is the typical architecture chosen for high efficiency diode pumped lasers. In this architecture, the diode pump light is imaged onto the end of a circular or square rod with simple lenses in such a way that the cavity mode and pump mode are colinear in alignment and matched in size. End-pumping is relatively difficult to scale to high powers. The large fiber bundle resulting from many diode/fiber pairs yields a large pump mode that often results in multi-transverse mode operation. The physical size of the laser cavity can be lengthened to expand the

cavity mode but this results in a cavity that is prone to mechanical vibration and creep. Additionally, thermal lensing may require the use of some intracavity compensating element to force stable and efficient operation at high pump powers.

The most severe problem encountered in scaling rod lasers to high power is the depolarizing effect of stress birefringence. As described in Koechner[1], the radial and tangential components of stress resulting from the expansion of a circular rod serve to depolarize light over a considerable portion of the rod cross sectional area. This effect results in both a power loss and reduction in beam quality when rods are used in high power, single frequency lasers. Several authors[3] have shown that stress birefringence can be reduced by the rectilinear pumping and cooling boundary conditions used in the zig-zag side-pumped slab laser.

We selected a pump configuration for this project that we hoped would combine the high mode coupling efficiency of the end-pumped rod with the reduced stress birefringence of a rectangular slab. Our rectangular slab is end-pumped from both ends by a high-aspect ratio, rectangular pump profile formed by the image of a rectangular array of 12 pump fibers. The pump loading can be made approximately uniform longitudinally by a correct choice of crystal length for a particular doping level and can be made uniform transversely over a substantial portion of the cavity mode, thereby achieving a temperature profile that more closely approximates the profile of a uniformly-pumped rectangular slab. For this project, we selected a rectangular pump profile approximately 1.8 mm wide by .6 mm high, formed by the 1:1 image of a 6 by 2 array of 300 micron fibers. The cavity mode is expanded in one direction to match the rectangular pump mode, achieving a theoretical mode coupling efficiency of 0.8 or better by using cylindrical optics within the laser cavity.

The cavity that we selected to utilize this pump profile is shown in Figure 2. Since the TEM_{00} cavity mode within the YAG slab must be highly asymmetric to couple to the rectangular pump mode (approximately 0.3 mm in half-height by 0.9 mm in half-width), a cylindrical beam-expanding telescope acting in the horizontal direction is used to provide this asymmetric mode profile. Two sections of expansion/contraction are used in the resonator, consisting of mirrors 1 and 2 acting as a pair and mirrors 4 and 5 acting as a pair.

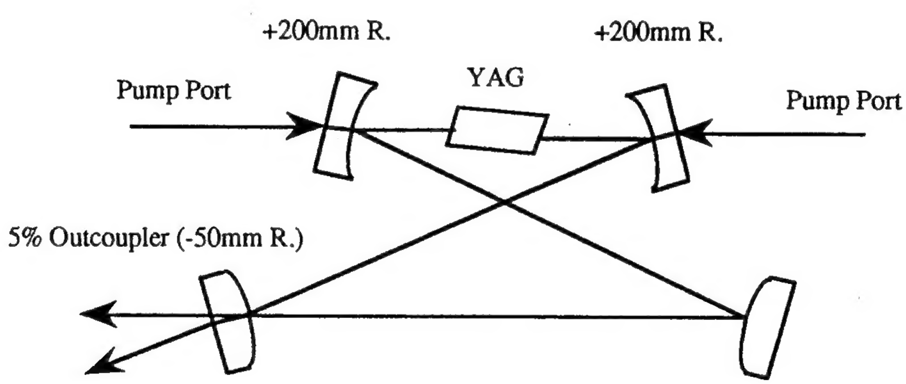

Figure 2. Cavity used for elliptical mode ring laser. Horizontal view shown. Optics are cylinders in the horizontal plane only. Thermal lensing stabilizes the cavity in the vertical direction. Cooling direction is normal to the horizontal plane.

Both tangential (horizontal plane) and sagittal (vertical plane) thermal lensing is included in modeling each YAG slab, and the resultant cavity mode profile along the cavity length is plotted in Figure 3. The use of cylindrical optics means that the cavity has the advantage of being adjustable in the horizontal and vertical planes independently. Indeed, the pump-dependent weak lens in the horizontal direction is compensated for by adjustment of the spacing of each expanding telescope. Since the cavity mirrors provided no focussing in the vertical plane, we depended on the thermal lensing in the vertical direction to stabilize the cavity. Our modeling showed that we could control the vertical and horizontal cavity mode sizes within the YAG block so that TEMoo operation would be expected at high pump power levels.

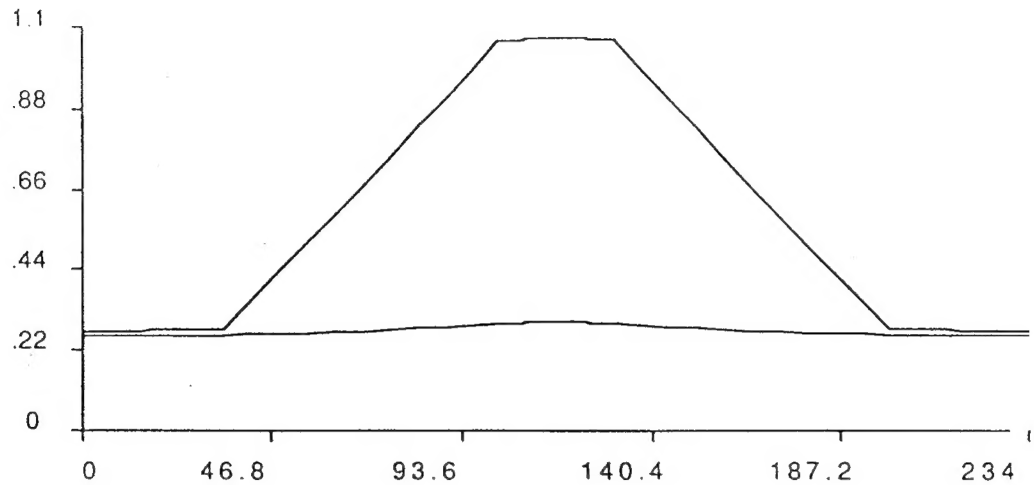

Figure 3. Mode radii in the vertical and horizontal planes in millimeters. The YAG slab is in the center of the cavity. The large radius mode is in the horizontal plane.

A ring cavity was selected since such a cavity will easily result in single-frequency operation if the ring is operated unidirectionally. A simple, intracavity Brewster-angled Faraday rotator is used as the non-reciprocal polarization rotator. The cavity elements are aligned such that the ring path is not a plane, thereby serving as a reciprocal polarization rotator. The combination of these two rotators yields unidirectional operation as per the theory described by Nillson [4].

Injection-locking, CW and Q-switched

C.W. injection locking has been shown[5] to be an effective means of controlling the frequency of a higher power slave laser oscillator with a lower power master laser oscillator. The master oscillator proposed for this task was the Lightwave model 120 non-planar, monolithic ring laser. This laser exhibits linewidths of typically a few tens of kilohertz and is temperature tunable over a a few tens of gigahertz. To be useful as an injection locking source, the laser must be carefully mode matched into the slave oscillator to overlap the mode profile of the anticipated TEMoo mode within the slave oscillator cavity. The locking process requires that the difference between the slave cavity frequency (and therefore, the slave cavity length) and the master oscillator frequency be controlled to within the locking range, typically a few megahertz. This is accomplished by means of the so-called Pound-Drever-Hall[6] phase sideband technique (Figure 4). Phase sidebands are placed on the master oscillator input illumination and the signal reflected

off of the slave oscillator cavity is measured and mixed with the electronic master oscillator used to create the phase sidebands. An error signal derived from the mixer output is then sent to a piezoelectric transducer that controls the length of the slave laser cavity. Sufficient gain and bandwidth are required to overcome the effects of mechanical vibrations on the passive frequency of the slave oscillator.

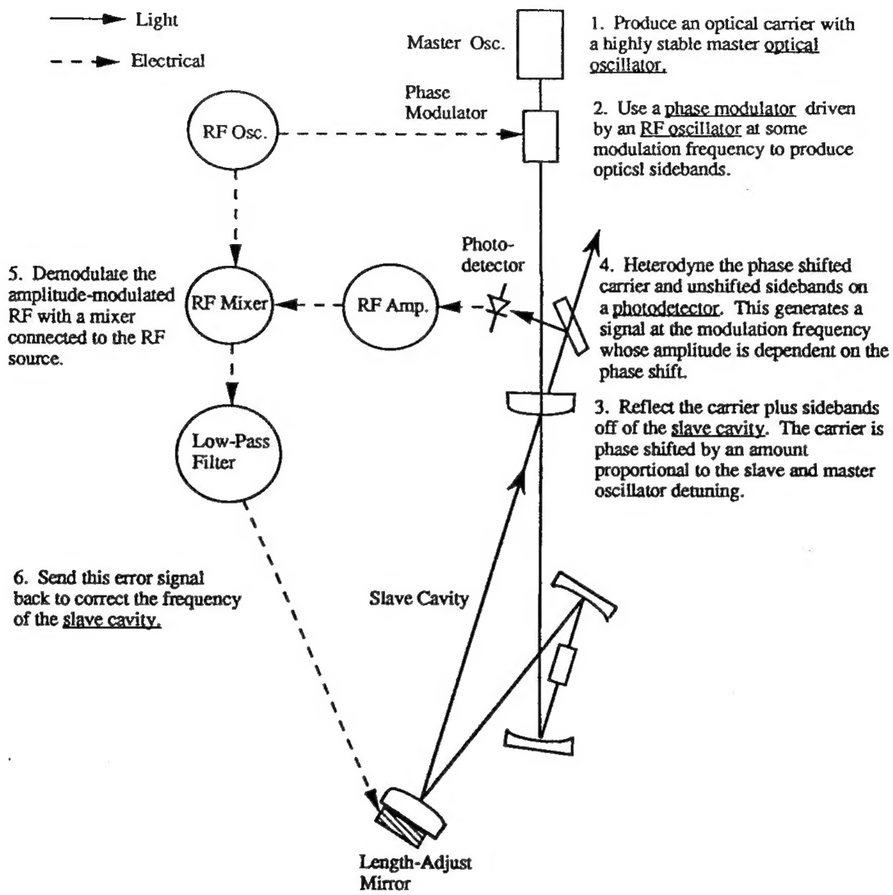

Figure 4. Block diagram of the Pound-Drever-Hall sideband locking technique. The technique is suitable for locking passive and active cavities to another oscillator (or vice versa). The slave cavity in this case is the end-pumped YAG ring laser.

The situation for Q-switched operation is essentially the same as that for C.W. locked operation, except that the cavity locking process must be performed while the slave laser is "off", that is, between Q-switched pulses. During this inter-pulse period, the Q-switch holds the slave cavity below threshold while energy is stored in the laser crystal. Indeed, the laser can be thought of as a low finesse passive cavity that is periodically and only momentarily flooded with a high intracavity fluence. The Pound-Drever-Hall locking process can still be made to work during these "off" periods except that the low cavity finesse alters the gain and bandwidth capabilities of the servo system. Additionally, the Q-switch drive level must be carefully adjusted during "off" periods to be high enough to keep the cavity away from free-running oscillation yet be low enough to yield a usable error signal to the cavity length control servo.

The block diagram of the overall system that we proposed is shown in Figure 5. The details of the laser head are shown in Figure 6.

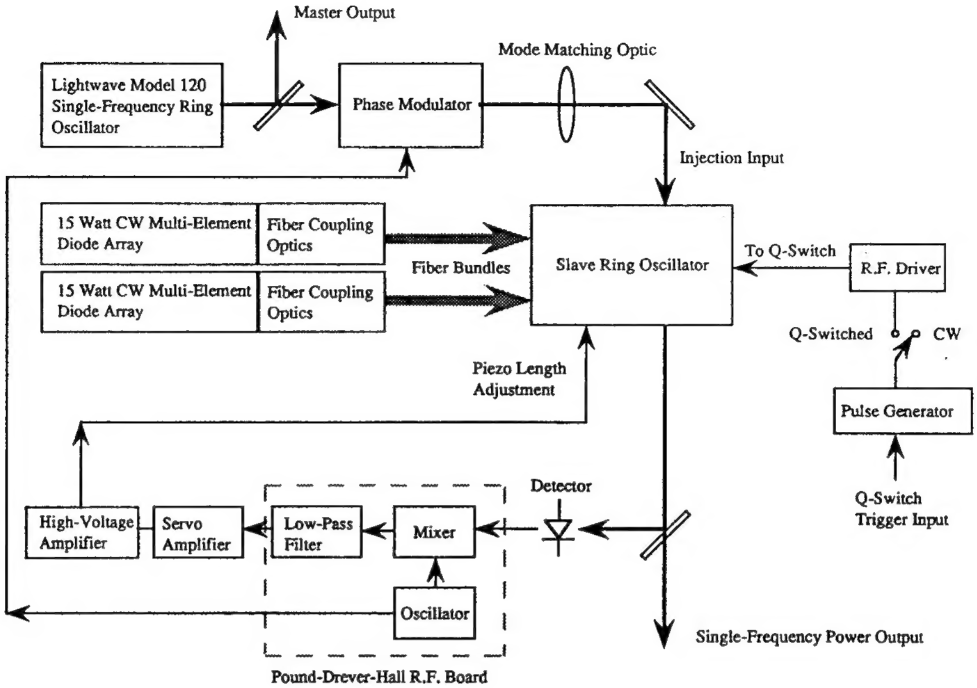

Figure 5. Block diagram of the proposed 5 watt injection-locked C.W. and Q-switched single-frequency laser.

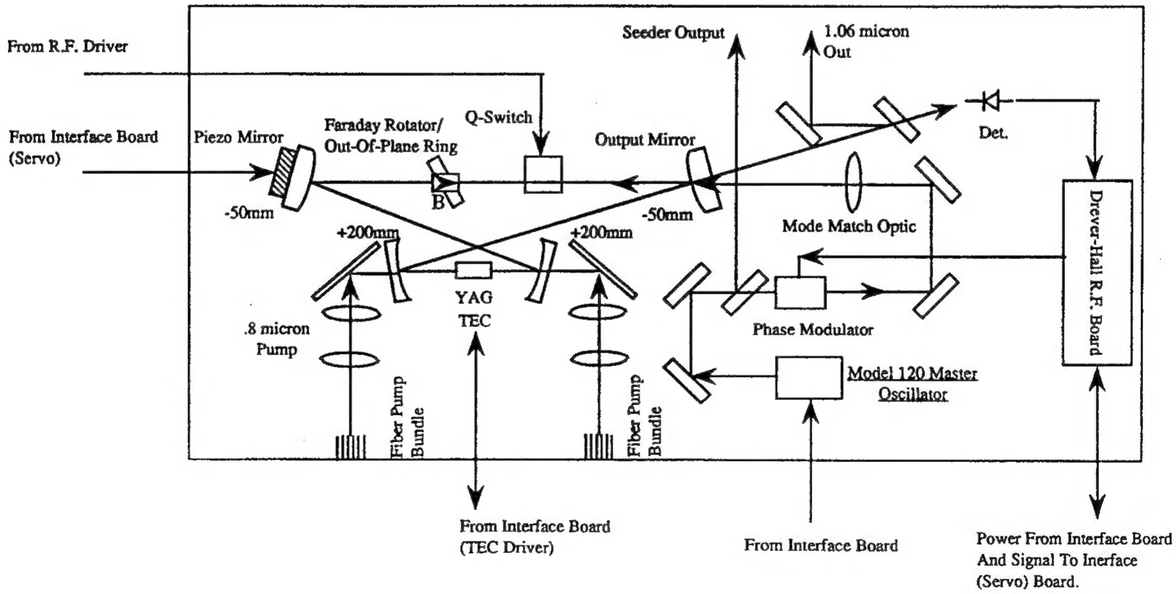

Figure 6. Layout of the laser head.

Results

Introduction

There were two distinct periods in the development of the system. The first stage was what might be called the "breadboard" stage, in which the system was built on a conventional optical table with the typical mirror mounts and adjustments found in most laser laboratories. This was also the period during which we used relatively low-power diode bars as a pump source. During this period, the system was spread out over a large fraction of a 4' by 8' optical breadboard which allowed easy access to the optical path. At this stage, only 2.5 to 3 watts of power output was typically achieved from the laser but otherwise, the laser performed well. Output was single-frequency with a TEMoo transverse mode profile and the slave laser could be easily locked to the master oscillator. The system could be tuned over 10 GHz or more by simply changing the temperature of the master oscillator and allowing the servo system to lock the slave to the master. Frequency-locked Q-switched operation was also easily obtained at any repetition rate from 0 Hz to 2 kHz. The electronics would allow automatic recovery from mechanical disturbances that would otherwise cause the master and slave to loose lock and not recover.

Although this early success was encouraging, we did not have the opportunity to test the system on the breadboard under high pump power operation. We already knew that the optical alignment of the system was time-consuming and tedious even at this point when the optical table allowed easy access to all points in the optical path for easy diagnosis. We anticipated that compressing all of the optical components into a rigid box with a greatly reduced number of optical adjustments might prove difficult. Additionally, the breadboard electronics assemblies built by this author had not been redesigned to their final stage before proceeding to the final system integration. However, because of time constraints, we chose to press ahead with a final system design without a full test of electronic assemblies and without a high-power pumping demonstration. This decision proved to be fatal to the project.

Pump Source

High-power, high-NA fiber is available from 3-M and this is the fiber we selected both for the fiber lens and for the fiber bundle. This fiber has a 300 micron diameter core with a 15 micron thin polymer cladding. The thin cladding is useful for the close spacings required by the emitter pattern of the diode array but it is also useful for constructing a fiber lens for collimation. The thin polymer cladding is easily dissolved in methylene chloride, resulting in a uniform index, 300 micron diameter silica rod lens. These lenses are then AR coated at the diode wavelength (808nm) and suspended in front of the diode emitters at a carefully optimized distance by using a conventional x-y-z translation stage with an additional rotation stage for angular positioning. The lens must be aligned parallel with all of the emitters over the entire 1 cm length of the array. The lens is soldered into place after carefully positioning the lens and observing the far-field illumination after the fiber lens. We discovered that, unless all of the fiber lens mounting components and the fiber itself are made from materials with the same coefficient of thermal expansion, the fiber cannot be fastened at both ends without inducing severe warping. Therefore, the fiber lens is rigidly mounted at one end only while the opposite end is supported within a stainless steel tube of just over 300 microns inside diameter. The fiber is thereby allowed to expand or contract in length while the fiber position remains unchanged relative to the face of the diode array.

After the lens is aligned, the fiber array was positioned in correct optical alignment. The individual polished and AR-coated fibers are placed side by side at the required spacing by placing

the fibers into an array of parallel steel tubes that have been previously aligned in a precision jig. The tubes are then soldered together while fixed within the jig. Individual damaged fibers may then be removed from this structure and replaced if needed. This entire structure is then aligned with another x-y-z stage and again soldered in place. Since the soldering takes place on a ceramic substrate with resistively-heated pads, the lens and fiber array can be removed and replaced if the alignment procedure needs to be repeated. This whole structure, while quite flexible in principle was not well implemented in the first iteration of hardware provided for the NVEOD laser and requires several tedious steps of assembly and reassembly in the event of diode bar or fiber failure. Several embarrassing "melt-downs" of this assembly damaged both fibers and diodes before design improvements reduced these failures. Additionally, the diode bars were not mounted in a sealed assembly, increasing the risk of diode optical facet damage. Subsequent versions of this design are much easier to assemble and less susceptible to diode bar damage. However, they were developed under a subsequent contract and have not been installed in the NVEOD system. Power for each diode bar is supplied by a commercially-available current-regulated supply. The diodes are mounted on thermoelectric coolers and the resultant heat is transported to a heat exchanger by closed-loop water flow.

Cavity Design

Early results with the cylindrical mode cavity were encouraging at low pump power levels. An early lab-bench version of our fiber coupling scheme utilizing a pair of 10 watt diode bars yielded approximately 8.5 to 9 watts from each fiber bundle. When this pump power was coupled into our cylindrical mode cavity, approximately 3 watts single-frequency output was provided by the oscillator. Although the slope efficiency achieved in these early experiments was only about 25%, we expected that slope efficiencies would improve as the vertical thermal lens increased to that expected in the computer model. Because of the delays in obtaining the fiber-coupled 15 watt bars, we were unable to verify the validity of our thermal lensing model until near the end of the project. When we did actually have the higher power diodes and fibers available for use, we found that our thermal lensing calculations were incorrect and that our cavity did not provide for enough expansion in the vertical direction to prevent multi-transverse mode operation without extremely delicate alignment. In fact, at this point, all single frequency and injection-locking features of the laser were doomed to failure without the ability to obtain dependable, single transverse mode operation.

We did however, determine that our rectangular pumping and cooling scheme did provide some decrease in stress-induced loss over results obtained with circular pumping. Single pass depolarization measurements showed that rectangular pumping/cooling could reduce intracavity loss by a factor of three over the results obtained with circular pumping/cooling.

Injection Locking and Frequency Stabilized Operation

Injection locking worked as planned on the lab breadboard but failed miserably in the final embodiment of the laser. As mentioned previously, TEMoo operation is essential for stable injection locked operation. Although the laser (in final form) could sometimes be made to operate single transverse mode at high power, it was then found to be very difficult to properly couple the mode from the injection laser into the mode of the slave laser without adding power into higher order transverse modes of the slave laser. This effect destroyed single transverse mode operation in the injection locked mode. This was partly caused by our imperfect knowledge of the mode size in the slave laser but also caused by our inability to make adjustments in the injected beam after the laser was installed in the final enclosure.

An additional problem that prevented adequate locking stability was not caused by optical

issues at all but was caused by insufficient bandwidth in our cavity length-control servo system. As shown in Figure 5, the servo consists of a Pound-Drever-Hall R.F. board, a servo amplifier, control electronics, a high voltage piezo driver and a piezo-mounted mirror. Specifically, we had insufficient bandwidth in both the servo amplifier and an insufficiently-high mechanical resonance frequency for the piezo-mounted mirror. On the laboratory table the mechanical resonance of our piezo-mounted mirror was high enough that, although there were some stability problems, the system could usually be adjusted to produce stable, yet somewhat noisy locked operation. However, we changed piezoelectric transducers for the final system assembly because we needed to achieve longer mirror motions to compensate for thermal expansion. This final piezo/mirror combination proved to have a resonant frequency too low to insure loop stability. As a result, the gain of the servo system could not be increased to a level sufficient to maintain locked operation between the slave and master oscillator against the perturbations caused by mechanical noise.

Even though the slave laser oscillator cavity has an intracavity unidirectional device, the ring oscillator can, for brief moments, operate in the reverse direction. In other words, the ring can momentarily send light backwards into the injection laser. This is not a problem when running in the CW mode, but it is disastrous when running Q-switched as the reverse-directed pulse will destroy the laser diode in the injection oscillator. This effect twice resulted in the destruction of the master oscillator pump diode.

Final Hardware

Since we found it impossible to injection lock the slave and master oscillator, we did not include some of the components required for this task in the final hardware. The master oscillator is included however, as it is essential for.

Normally, the injection locking process forces the oscillator to run single frequency. Without this control, the ring laser may hop between adjacent longitudinal modes. A solid etalon has been installed in the cavity to insure single-longitudinal-mode oscillation. However, the etalon is not automatically "locked" to a longitudinal mode so periodic readjustment of the etalon is required to compensate for thermal drift of the cavity. The operating manual supplied with the laser describes the procedure for monitoring the laser performance and adjusting the etalon.

Q-switched operation is also possible yet we have found that stable single frequency operation is not possible above a repetition rate of about 2 kHz. We believe that there is no fundamental reason that this rate cannot be increased, but there was insufficient time remaining to diagnose the problem. The Q-switch must be installed and adjusted by the user when converting from C.W. operation. We found that it was not possible to leave the Q-switch in the cavity at all times as the insertion loss was excessive for efficient C.W. operation.

Originally, we anticipated that the cavity could be aligned, back-filled with dry air and sealed. The need for cavity adjustments by the user prevented the use of this feature. Additionally, the locking electronics and various components that were to be placed in the laser head that were an integral part of the locking feature were not included. As a result, the final version of the laser head is considerably larger and more complicated than would normally be needed for the reduced performance offered by the final laser package.

Possible Improvements

Considering what we have learned in the process of developing and experimenting with this laser system, there are several things that we would do differently if we had a fresh sheet of paper to start over.

Cavity Design

We would expect that we could still use 15 watt fiber-coupled bars as a pump source, incorporating the improvements in assembly techniques that we have developed on a subsequent contract. At the 5 watt level, stress birefringence is acceptable with circular end-pumped rods. Recently we have achieved 3.3 watts output from a simple end-pumped ring cavity using a single 15 watt fiber-coupled bar. Although this experiment uses two bundles of 6 fibers each from the 12 fibers available from the bar, we believe that we might be able to scale the laser to the 6 watt level with two bundles of 12 fibers from two diode bars. The greatest difficulty will be in expanding the cavity mode to a size sufficient to prevent multi-transverse mode operation.

Servo

We have improved the performance of both our servo amplifiers and piezo mirrors to enable high gain and good bandwidth. We have made considerable improvements in the R.F. portion of the Pound-Drever-Hall electronics to reduce the potential for feedback, drift in mixer output with temperature and susceptibility to distortion in the error signal caused by R.F. coupling between various components on the printed circuit board. In conjunction with an optical isolator between the master and slave oscillator, we expect that injection locking would not be a problem for a future design

Q-switched Operation

We would not attempt to construct a "one cavity does all" system in the future. We would either build an injection-locked single-frequency ring for C.W. use or an injection-seeded linear cavity for Q-switched operation. Both cavities could use the Pound-Drever-Hall technique, enabling pulse-on-demand operation for Q-switched operation.

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